# DISCOVERY OF SINGLE TOP QUARK PRODUCTION

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The first observation of electroweak single top quark production was recently reported by the the DØ and CDF collaborations based on 2.3 and 3.2 fb$^{-1}$ of $p\bar{p}$ collision data collected at $\sqrt{s} = 1.96$ TeV from the Fermilab Tevatron collider.[1,2] Several multivariate techniques are used to separate the single top signal from backgrounds, and both collaborations present measurements of the single top cross section and the CKM matrix element $|V_{tb}|$.

## 1   Introduction

The top quark was discovered at the Fermilab Tevatron in 1995[3] and is the heaviest elementary particle found so far. At the Tevatron, top quarks are predominantly produced in pairs via the strong interaction, but can also be produced singly via an electroweak $Wtb$ vertex. The two main single top production modes are the $s$-channel ($tb$) and the $t$-channel ($tqb$) processes illustrated in Figure 1. The analyses presented herein assume $\mathcal{B}(t{\rightarrow}Wb) = 1$, and that the $s$- and $t$-channel modes are produced in the standard model (SM) ratio. CDF uses $m_{\mathrm{top}} = 175$ GeV throughout the analysis, for which the NLO SM single top cross section $\sigma_{s+t}$ is 2.86 pb.[4] DØ use $m_{\mathrm{top}} = 170$ GeV for which $\sigma_{s+t} = 3.46$ pb at (N)NLO.[5]
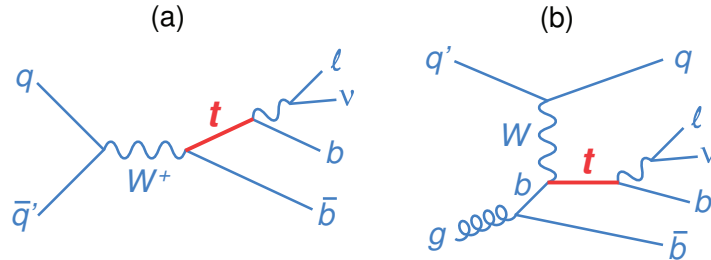


Figure 1:   Representative Feynman diagrams for (a) $s$-channel and (b) $t$-channel single top production showing the top quark decays of interest.

## 2  Motivation

Studies of single top quark events will provide access to properties of the $Wtb$ coupling,[6] such as the CKM matrix element $|V_{tb}|$ (see Section 7). Single top quark production is also a very important background for SM Higgs production, and studies of the single top final state offer potential for several discoveries beyond the SM.[7] For instance, the existence of a new heavy boson (like a charged Higgs) would enhance the single top $s$-channel cross section while the existence of flavour-changing neutral currents could enhance the $t$-channel cross section.

## 3  Analysis Strategy

The analyses start by selecting events where the $W$ boson from the top decays leptonically. Due to the small single top cross section and the large background (mainly from $W$+jets processes and $t\bar{t}$), a simple cut-based counting experiment is not sufficient to verify the presence of single top. Instead, the strategy used is to apply a fairly loose event selection and employ sophisticated multivariate techniques to extract the single top signal from the large backgrounds.

## 4  Dataset and Event Selection

The DØ collaboration uses a larger dataset and a looser event selection compared to the previous analysis,[8] which reported the first evidence for single top quark production. The 2.3 fb$^{-1}$ dataset was collected with the DØ detector using a logical OR of many trigger conditions. The main event selection criteria applied are an isolated electron or muon with $p_T > 15$ GeV, $\not{E}_T > 20$ GeV, 2-4 jets with $p_T > 15$ GeV out of which one jet has $p_T > 25$ GeV and at least one jet must be tagged with a neural network based $b$-tagging algorithm. Additional selection criteria remove multijet background events with misidentified leptons. The numbers of predicted events and the numbers of events observed in data are presented in Table 1.

The CDF collaboration constructs a 3.2 fb$^{-1}$ $\ell$+jets dataset using a similar, but slightly more stringent, event selection than the one used by DØ. Events are required to have an isolated electron or muon with $p_T > 20$ GeV, $\not{E}_T > 25$ GeV and 2-3 jets with $p_T > 20$ GeV. CDF also constructs a $\not{E}_T$+jets dataset that accepts events where the $W$ boson decays to a $\tau$ lepton, and those in which the electron or the muon fail the lepton identification criteria. Events with any isolated lepton are rejected, and events are required to have $\not{E}_T > 50$ GeV, one jet with $p_T > 35$ GeV, a second jet with $p_T > 25$ GeV, and $\Delta R > 1.0$ between the two leading jets. Additional requirements are applied to reduce the large instrumental background.[2] The number of events observed in the data and predicted by the modelled background and SM signal are presented in Table 1.

Table 1:  Predicted and observed numbers of events in the DØ and CDF datasets for single top ($tb+tqb$), the different background components and the data. $W$+jets is the largest background and is split into events with heavy flavour jets ($W$+HF) and events with fake $b$-jets (mistags) in the right table below.

| DØ | $\ell$+jets | | CDF | $\ell$+jets | $\not{E}_T$+jets |
|---|---|---|---|---|---|
| $\mathcal{L}$ [fb$^{-1}$] | 2.3 | | $\mathcal{L}$ [fb$^{-1}$] | 3.2 | 2.1 |
| $tb + tqb$ | $223 \pm 30$ | | $tb + tqb$ | $191 \pm 28$ | $64 \pm 10$ |
| $W$+jets | $2647 \pm 241$ | | $W$+HF | $1551 \pm 472$ | $304 \pm 116$ |
| $t\bar{t}$ | $1142 \pm 168$ | | $t\bar{t}$ | $686 \pm 99$ | $185 \pm 30$ |
| multijet | $300 \pm 52$ | | mistags, multijet | $778 \pm 104$ | $679 \pm 28$ |
| $Z$+jets, dibosons | $340 \pm 61$ | | $Z$+jets, dibosons | $171 \pm 15$ | $171 \pm 54$ |
| Total prediction | $4652 \pm 352$ | | Total prediction | $3377 \pm 505$ | $1404 \pm 172$ |
| Observed | 4519 | | Observed | 3315 | 1411 |

## 5    Signal-Background Separation

After the event selection, the expected signal is smaller than the uncertainty on the background (see Table 1). Both collaborations use several different multivariate techniques to further improve the discrimination against the background. Each such multivariate technique constructs a powerful discriminant variable that is proportional to the probability of an event being signal. The discriminant distribution is used as input to the cross section measurement. Several validation tests are conducted by studying the discriminant output distributions in background enriched control samples.

The DØ collaboration uses three individual techniques to separate single top quark events from the background, namely boosted decision trees (BDT), matrix element method (ME) and Bayesian neural networks (BNN). The BDTs use 64 well-modelled input variables and classify events based on the outcome of a set of binary cuts. Boosting is used to further improve the performance. The ME method calculates a discriminant by relating the reconstructed four momenta in the event with the expected parton-level kinematics. The BNN is an average of several hundred neural networks, and is constructed using 18-28 input variables. The three multivariate techniques are combined separately for each analysis channel using a second layer of Bayesian neural networks. The combined discriminant (Figure 2) gives a higher expected significance than any of the three individual discriminant methods on their own.

The CDF collaboration analyses their $\ell$+jets dataset using five different multivariate techniques: BDTs, neural networks, the ME method and two separate likelihood functions. The BDTs use 20 input variables, the NN analysis constructs four separate NNs from 11-18 input variables, and the ME analysis calculates the signal probability from Feynman diagrams. Two projective likelihood functions are constructed using 7-10 input variables; the LF discriminant is optimized to find single top quark events in the whole dataset just like the other analyses, while the LFS discriminant is optimized to be sensitive to the $s$-channel process for events with two $b$-tagged jets. The five $\ell$+jets analyses are combined using a neural network trained with neuro-evolution,[9] which is tuned to maximize the expected significance. The combined discriminant is shown in Figure 2. CDF also constructs an MJ discriminant from the $\not{E}_T$+jets dataset using neural networks.
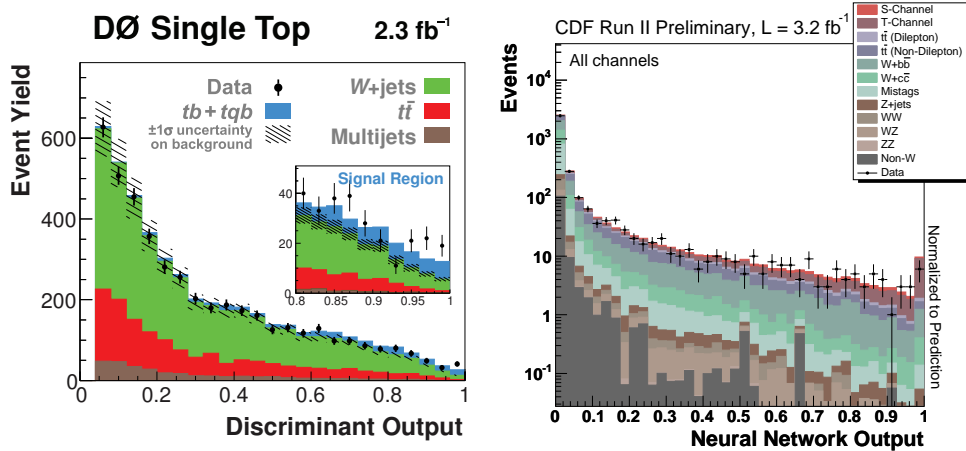


Figure 2:    Combined super discriminants for DØ (left) and CDF (right).

## 6    Results

Both experiments measure the single top quark production cross section from the discriminant output distributions using a Bayesian binned likelihood technique.[10] The statistical and all systematic uncertainties and their correlations are considered in these calculations. The measurements for each individual analysis and for all analyses combined are presented in Table 2.

DØ estimates the significance of the measurements from a large ensemble of pseudo experiments (PE) generated from background only with all uncertainties included. The cross section is measured for each PE, and the expected and observed $p$-values are calculated as the fraction of PEs giving a cross section equal to or higher than the SM $\sigma_{s+t}$ and the measurement in data respectively. CDF also generates large ensembles of PEs and obtain the expected and observed $p$-values by computing the log-likelihood ratio test statistic [2] for each PE. The $p$-values are converted into a number of Gaussian standard deviations, and are presented in Table 2.

Table 2: Integrated luminosities, expected and observed significances stated in standard deviations $\sigma$ and measured single top cross sections for the DØ (left) and CDF (right) analyses. [†] LFS measures $\sigma_s$, not $\sigma_{s+t}$.

| CDF Analysis | $\mathcal{L}$ [fb$^{-1}$] | Significance Exp. | Obs. | Measured $\sigma_{s+t}$ [pb] |
|---|---|---|---|---|
| BDT | 3.2 | $5.2\sigma$ | $3.5\sigma$ | $2.1^{+0.7}_{-0.6}$ |
| NN | 3.2 | $5.2\sigma$ | $3.5\sigma$ | $1.8^{+0.6}_{-0.6}$ |
| ME | 3.2 | $4.9\sigma$ | $4.3\sigma$ | $2.5^{+0.7}_{-0.6}$ |
| LF | 3.2 | $4.0\sigma$ | $2.4\sigma$ | $1.6^{+0.8}_{-0.7}$ |
| LFS | 3.2 | $1.1\sigma$ | $2.0\sigma$ | $1.5^{+0.9}_{-0.8}$ [†] |
| MJ | 2.1 | $1.4\sigma$ | $2.1\sigma$ | $4.9^{+2.5}_{-2.2}$ |
| Combined | 3.2 | $> 5.9\sigma$ | $5.0\sigma$ | $2.3^{+0.6}_{-0.5}$ |

| DØ Analysis | $\mathcal{L}$ [fb$^{-1}$] | Significance Exp. | Obs. | Measured $\sigma_{s+t}$ [pb] |
|---|---|---|---|---|
| BDT | 2.3 | $4.3\sigma$ | $4.6\sigma$ | $3.74^{+0.95}_{-0.79}$ |
| BNN | 2.3 | $4.1\sigma$ | $5.4\sigma$ | $4.70^{+1.18}_{-0.93}$ |
| ME | 2.3 | $4.1\sigma$ | $4.9\sigma$ | $4.30^{+0.99}_{-1.20}$ |
| Combined | 2.3 | $4.5\sigma$ | $5.0\sigma$ | $3.94^{+0.88}_{-0.88}$ |

## 7  Measurement of $|V_{tb}|$

Both DØ and CDF use their cross section measurements to extract $|V_{tb}|$. This is possible since the single top cross section is directly proportional to $|V_{tb}|^2$. Under the assumptions stated in Section 1, CDF measures $|V_{tb}| = 0.91 \pm 0.11(\text{stat+sys})\pm0.07(\text{theory})$ and sets the limit $|V_{tb}| > 0.71$ at 95% CL. Assuming $m_{\text{top}} = 170$ GeV (Section 1), DØ extracts the limit $|V_{tb}| > 0.78$ at 95% CL, and measures $|V_{tb}f_1^L| = 1.07 \pm 0.12$, where $f_1^L$ is the strength of the left-handed $Wtb$ coupling.

## 8  Summary

The DØ and CDF collaborations have performed precise measurements of the electroweak single top quark production cross section and the CKM matrix element $|V_{tb}|$ using 2.3 fb$^{-1}$ and 3.2 fb$^{-1}$ of data respectively. Both collaborations individually observe a 5.0 standard deviation excess over background in their data and thereby establish the discovery of single top quark production.

## References

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